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DETERMINATION OF NORMAL DRAG COEFFICIENTS FOR FLEXIBLE CABLES

PHASE REPORT
AIRTASK NO. A37533000/2021/F101-13-07
Work Unit No. 170

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DEPARTMENT OF THE NAVY
U. S. NAVAL AIR DEVELOPMENT CENTER
JOHNSVILLE
WARMINSTER, PA. 18974

Aero-Electronic Technology Department

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The determination of normal drag coefficients for flexible cables was developed to aid in a study of static cable drag dependence on cable strumming as related to underwater suspension cables used with airborne ASW sonar systems.

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SUMMARY

INTRODUCTION

The determination of normal drag coefficients for flexible cables has been an art instead of a science because of the bizzare vibration modes of flexible cables in a fluid stream. These cable vibrations are commonly termed cable strumming. The difficulty arises because the drag is dependent on the amplitude and frequency of the cable vibration and an adequate understanding of the vibration modes is necessary to intelligently determine the cable drag. These modes have been studied[1, 2] and found to be basically defined by the classical vibrating string and Strouhal concepts.

A technique for the determination of the normal drag coefficient for a flexible cable is to be developed. The technique is to aid in a study of static cable drag dependence on cable strumming as related to underwat suspension cables used with airborne ASW sonar systems.

RESULTS

Normal cable drag coefficients were determined from a static balance of coplanar fluid and gravity forces after measuring the cable drag angle of a towed streaming test cable with a terminal sphere standard. Cable strumming characteristics were determined and used to diagnose the cable vibration modes for selecting appropriate data points. Normal drag coefficients were determined for circular flexible cables from 0.057 to 0.140 inches in diameter, within the Reynolds number range 300 to 1300, and 0.2 to 1.2 kn velocity.

A parametric analysis was made of the estimated errors inherent in the technique. Maximum, limiting, and absolute error in the normal drag coefficient was predicted to fall between 10 and 20 percent. Probable experimental errors were between 5 and 10 percent.

CONCLUSIONS

A general method for determination of the normal drag coefficient of a strumming flexible cable has been developed. The technique considers the cable drag dependence on the flow induced cable vibrations and is applicable to all flexible cable designs including faired and nonfaired types.

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1. *Dale, J. R. and Menzel, H. R., Dec 1965; Flow Induced Oscillations of Hydrophone Cables; NAVAIRDEVCEN; 23rd Naval Underwater Sound Symposium Proceedings, ONR Rpt ACR-115, Paper 3A6, Pg 411.*
2. *Dale, J. R. et. al. Sep 1966; Dynamic Characteristics of Underwater Cables - Flow Induced Transverse Vibrations; Report No. NADC-AE-6620.*

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LIST OF SYMBOLS

A, B - Experimental constants

C_D - Dimensionless normal cable drag coefficient

C_{Ds} - Dimensionless normal cable drag coefficient based on d for normal flow past a strumming cable

D - Terminal sphere diameter

d - Cable diameter

F - Alternating periodic strumming force which accelerates the fixed end mass

F_u - Drag force on terminal sphere

f - Frequency of the transverse cable vibrations

f_c - Normal drag force per unit length of the cable

g - Gravitational constant

k - Spring constant of cable in transverse direction

L - Cable length

ℓ - Total moment arm of cable forces

M_o - Moment

m - Fixed end mass

m_c - Virtual cable mass per unit length (physical mass plus mass of an equivalent volume of water)

N_{Re} - Dimensionless Reynold's number = du_o/ν

n - Number of vibrating cable segments in the cable length L. $n = L/\ell$

S_t - Dimensionless Strouhal number = fd/u_o

T - Tension in the cable

LIST OF SYMBOLS (continued)

t - Time

u_n - Component of water velocity normal to the cable

u_o - Free stream water velocity

W - Weight of the terminal sphere in water

w_c - Weight per unit length of cable in water

y - Displacement of end mass

$\ddot{y}$ - Acceleration of end mass

α_1 - Tangent angle at the tow point

α_2 - Tangent angle at the terminal mass

ν - Viscosity constant

ρ - Density of water

θ - Cable angle with horizontal

θ_c - Correction angle increment

ω - Angular forcing frequency

DISCUSSION

BACKGROUND

To determine meaningful values for the normal drag coefficient of a flexible cable an understanding of the physics of cable strumming is essential. The results of two recent studies[1 2] are summarized below.

Transverse standing wave cable vibrations are excited by the interaction of the water flow relative to a flexible cable. When the flow velocity is gradually changed, transitions in amplitude and frequency occur at discrete velocities each time the number of standing wave segments changes by one. The frequency interval between successive transitions and a specific standing wave segment length characterizes a numbered partial vibration mode. (The term partial is used instead of harmonic because the frequencies are not even multiples of the fundamental.) The vibration modes are defined by the string equation

$$L = \frac{n}{2f}\sqrt{\frac{T}{m_c}} \qquad (1)$$

where the forcing frequency is approximately defined by the Strouhal number,

$$S_t = fd/u_o \qquad (2)$$

The amplitude of each standing wave vibration is a minimum near the transitional water velocity, frequently zero. Within each partial mode, a maximum amplitude is reached when the excitation frequency approximately equals the natural cable frequency of each vibrating segment. The normal drag coefficient is directly dependent on these amplitude variations.

CABLE DRAG COEFFICIENT

An experimental technique has been developed to determine C_{Ds} by towing a test cable through water. The lower free end of the test cable was attached to a smooth surfaced sphere used as a standard, of known weight and known velocity dependent drag force. The cable drag angle at the tow point (fixed end) was measured and corrected for the bow in the streaming cable. The normal water force per unit cable length was then determined by summing the force moments about the tow point. Using this force and the cable diameter, C_{Ds} was computed.

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1. *See pg iii.*
2. *See pg iii.*

The accuracy of the C_{Ds} determination is enhanced by a prudent selection of cable length and drag to weight ratio of the sphere standard. Cable lengths from 3 to 4 ft were used because longer cables generally are excited with multiple frequency beating effects which obscure the signature of the strumming signal. A 2-in. diameter smooth sphere weighing 0.504 lb (in water) was used as a standard.

CABLE STRUMMING FORCE

The periodic strumming forces, equivalent to cable tension oscillations, were determined by measuring the accelerations of a spring mounted mass. The mass and spring supported the cable at the tow point. The spring constant and mass were selected such that the spring restoring force was small compared to the force to accelerate the mass. Accordingly, the force determination is essentially the product, mass times acceleration.

DATA ACQUISITION

The instrumentation, mounted at the tow point, to determine C_{Ds} and F is illustrated in figure 1. The test cable was towed by a rotating arm with a 7-ft radius. During each test the angular velocity of the arm was varied such that the free stream tow velocity gradually decreased from about 1.2 to 0 kn in about 2 min. This provided data over the N_{Re} range of interest which spanned several partial vibration modes.

A segment of the raw data recording, for a 0.107 in. diameter cable, 36 in. long, is illustrated on figure 2. The water flow is decreasing uniformly from 1.0 to 0.2 kn. Observe the 3 partial vibration modes indicated by the 3 triangular forms of the acceleration signal. Starting from the high velocity end, these modes correspond to the fourth, third and second partials with half wave lengths of 9, 12, and 18 in., respectively. The trace of the cable drag angle is seen to hump during these partial vibrations, indicative of an increase in cable drag.

The C_{Ds} (based on 0.107-in. diameter) and the periodic strumming force are plotted against N_{Re} on figure 3. The normal drag coefficient for a nonstrumming circular cylinder is plotted for a reference. Each saw tooth form represents a discrete partial vibration. The minimum points are taken between the partials or near the transitions where the cable vibrations have decayed to a low level. Notice the minimum points approach the C_D reference plot.

The peak values correspond to the high level acceleration signals which are related to the transverse cable vibration amplitudes. For a specific partial mode, the highest C_{Ds} value is found at the velocity corresponding to these peak signals. The maximum and minimum points of these sawtooth characteristics will occur at different N_{Re} if the cable length is changed. This can be seen from equation No. 1 where a change in L will result in a different f for the same numbered partial, n. The

water forcing function will excite the cable at this new f at a different velocity or N_{Re}. The peak values of the parameters, therefore, describe an envelope which is independent of cable length. (Envelope values will be inferred with reference to C_{Ds} and F for the remainder of the report).

The drag angles that correspond to these envelope points, for a specific cable length, are usually found where the drag angle trace humps for each partial vibration mode. The humps usually correspond to peak values of the strumming signal. To aid in choosing envelope data the strumming signal should be recorded simultaneously with the cable drag angle signal. It is not necessary to calculate the strumming forces from the acceleration signals for the purpose of choosing envelope data. The velocities corresponding to the envelope data points can be selected using the acceleration trace. Therefore, a prerequisite for determining the drag coefficient envelope is to obtain continuous data of drag angle, strumming accelerations and water velocity over one or more partial vibration mode. The drag coefficient may be more sensitive to water velocity for unusual cross-sectional cable designs and it is good practice to evaluate the drag coefficient values over the velocity range of interest.

DRAG COEFFICIENT PREDICTION

Recent work relative to the dependence of cable drag on cable strumming has resulted in a scaling law to predict the C_{Ds}. The law is applicable to smooth flexible cables with circular sections. The C_{Ds} is equivalent to a factor times the nonstrumming coefficient or,

$$C_{Ds} = C_D \left[1 + 10 \left(d^2/\dot{m}_c\right)^2\right] \tag{3}$$

This concept has been verified for cables from 0.057 to 0.140-inches in diameter over a N_{Re} range of 300 to 1300.

DRAG COEFFICIENT CALCULATION

The experimental technique employed to measure the C_{Ds} of a flexible cable is based on a balance of the static force moments acting on the cable and terminal sphere. Figure 4 illustrates the forces involved in the static balance where the cable is assumed to stream in a straight line between the fixed end and the sphere.

The moment associated with the normal drag force per unit length of cable is given by:

$$\curvearrowright M_o (f_c) = \int_{L-\ell}^{L} f_c y dy = f_c \ell \,(L - \ell/2) \tag{4}$$

The moment associated with the cable weight is given by:

$$M_o\ (w_c) = \int_{L-\ell}^{L} w_c\ y\ \mathrm{Cos}\ \theta\ dy = w_c\ \mathrm{Cos}\ \theta\ (L-\ell/2) \tag{5}$$

Summing all the moments about point o, yields:

$$\Sigma M_o = o = F_u\ L\ \mathrm{Sin}\ \theta + f_c\ \ell\ (L-\ell/2) - WL\ \mathrm{Cos}\ \theta - \tag{6}$$

$$w_c\ \ell\ \mathrm{Cos}\ \theta\ (L-\ell/2)\ f_c = w_c\ \mathrm{Cos}\ \theta + \frac{W\ \mathrm{Cos}\ \theta - F_u\ \mathrm{Sin}\ \theta}{\ell(1-\ell/2L)}$$

Since the normal water force per unit length of cable, where the cable is at an angle θ with the horizontal, is:

$$f_c = C_{Ds}\ d\ \frac{\rho}{2g}\ (u_o\ \mathrm{Sin}\ \theta)^2 \tag{7}$$

then

$$C_{Ds} = \frac{f_c}{\frac{d\rho}{2g}\ (u_o\ \mathrm{Sin}\ \theta)^2} \tag{8}$$

Since the tangent angle, α, is measured, a correction angle increment θ_c must be added to $(90 - \alpha_1)$ to account for the bowing effect of the flexible cable, thereby obtaining a corrected value for θ. By assuming the cable curvature to represent an arc length of a circle the value of θ_c is derived from the angle relations illustrated on figure 4B.

A sample data sheet used to calculate C_{Ds} is illustrated in figure 5 along with a typical calculation taken from the data presented. The sequential calculation steps to be followed conform to the format of the data sheet and are outlined below.

1. After the setup constants are identified, the measured parameters for each selected data point are entered.

2. The angle correction tabulation is completed as identified by the column headings to obtain the angle θ.

3. The C_{Ds} calculation tabulation is completed as indicated by the column headings to obtain the C_{Ds} value.

The periodic variation in the static tension is shown plotted as F in figure 3. As discussed previously, it is not necessary to calculate F since the recorded acceleration signal is proportional to F. Since the static tension oscillations are more meaningful than accelerations of a reference mass, the calculation is outlined as follows: The motion of the fixed end is considered to be a forced spring-mass system with negligible damping. The natural frequency is always less than the forcing frequencies. The equation of motion is:

$$m\ddot{y} + h_y = F \cos \omega t \qquad (9)$$

Since $\ddot{y}$ will be maximum when $\cos \omega t = \pm 1$ and $\ddot{y}_{max} = (2\pi f)^2 y_{max}$, equation 9 reduces to:

$$F = \pm \ddot{y} \left[\frac{k}{(2\pi f)^2} + m \right] \qquad (10)$$

The acceleration level and signal frequency are taken at the selected data points.

SELECTION OF TEST PARAMETERS

Selection of the independent test parameters (L, F_u, W, u_o and θ) was based on both the signal characteristics and the allowable error. The cable lengths used were less than 4 ft since longer cables are usually excited at multiple frequencies and the associated beat effects obscure the shape of each partial structure. When the partial structure is obscured, the selection of data points, corresponding to envelope values, is difficult. The cable must be long enough to be excited in at least 3 partial modes to adequately define the drag coefficient envelope. A cable length of 3 ft has been satisfactory for cables up to 0.2-in. diameter tested in the 0 to 1 kn velocity range. The sources of error inherent in the technique are:

1. Inaccuracy in measuring the physical system constants (w_c, W, F_u, ℓ, L, and d).

2. Assumptions made regarding the drag angle correction concept.

3. Measurement error in the test variables u_o and θ.

An estimate of the overall error was obtained by considering the magnitude of each of these sources. First, the precision of the physical system constants can be controlled by the experimentor to be a negligible weighted portion of the more dominant sources. The constants were generally considered good to 1 percent.

Secondly, an error in the drag angle correction concept is inherent because the bowed cable geometry departs from the assumed arc length of a true circle. The error is assumed to increase with the magnitude of θ_c and is estimated as 5 percent of θ_c.

Third, the error in the calculated value of C_{Ds}, relative to the estimated individual errors in u_o and θ, was analyzed by obtaining an expression for the total differential of equation 8. A measurement error of ± 2 percent of 1.0 kn was chosen as the overall measurement error in u_o. This is based on the error inherent in the measurement and readout of u_o. An estimated measurement error of 0.3 deg (2 percent of full scale-assumed as 15 deg), together with the stated 5 percent drag angle correction error comprise the total estimated error for θ. Using these error values and the nominal physical values (figure 5) for the experimental setup, limiting error curves were drawn for the useful ranges of u_o and θ. The curves are illustrated in figure 6. The curves represent upper limit errors in C_{Ds} since the individual errors in θ and u_o were always summed so as to give the maximum error in the drag coefficient. If a coefficient of 1.0 is computed for a given θ and u_o, and the coordinate point (θ, u_o) falls below the 10 percent curve, the experimental error is greater than 10 percent; if the point (θ, u_o) is above the 20 percent curve, the error is less than 20 percent. The area above the respective curves, therefore, defines a C_{Ds} error less than the limit indicated. The experimental data points were considered acceptable when they fell between the two limiting curves since the experimental error is probably between 5 and 10 percent of the drag coefficient value. The position of these plots is dependent on the choice of the physical system constants. Accordingly, the curves are valid only for the constants used (figure 5). An attempt was made to determine the position sensitivity of the curves to the cable diameter and the terminal sphere's drag to weight ratio.

1. Cable diameter, d: increasing the diameter resulted in lowering the limiting curves.

2. Drag to weight ratio: increasing the ratio again results in lowering the limiting curves; however, the normal velocity range would be reduced since the increased drag on the sphere results in higher tangent angles, α_1, at the tow point. The 2 in. diameter 0.504 lb (water weight), smooth sphere was chosen as a suitable standard for the experimental setup employed.

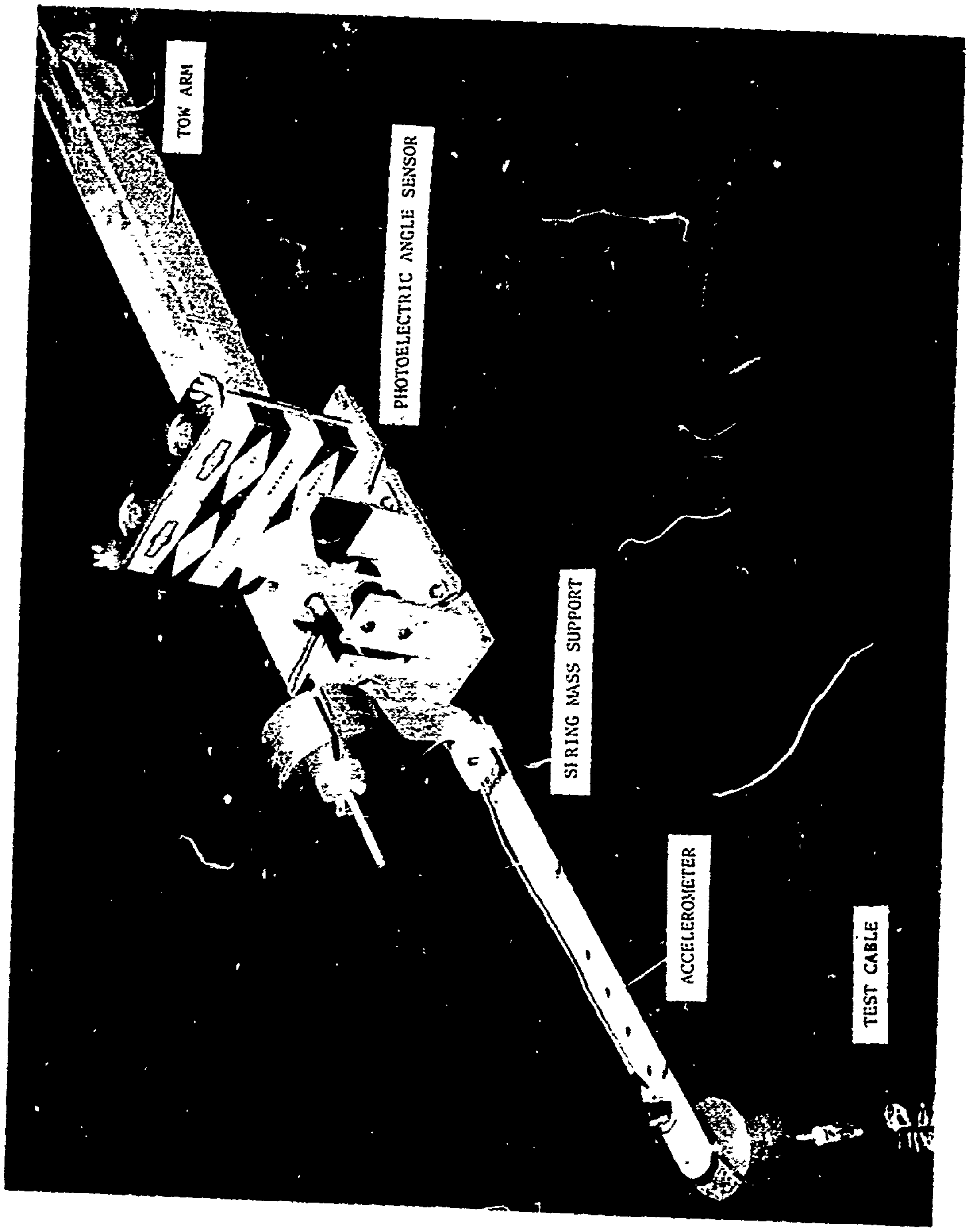


FIGURE 1 - Instrumentation for Measurement of Cable Drag Angle and Strumming Accelerations

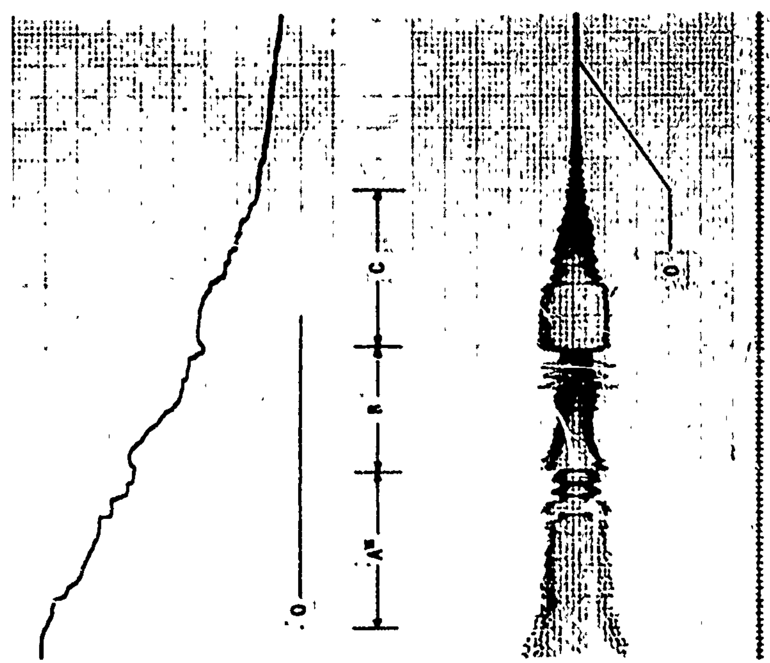


FIGURE 2 - Strumming and Drag Angle Signatures for a 0.107 In. Diameter Cable in a Gradually Decaying Flow

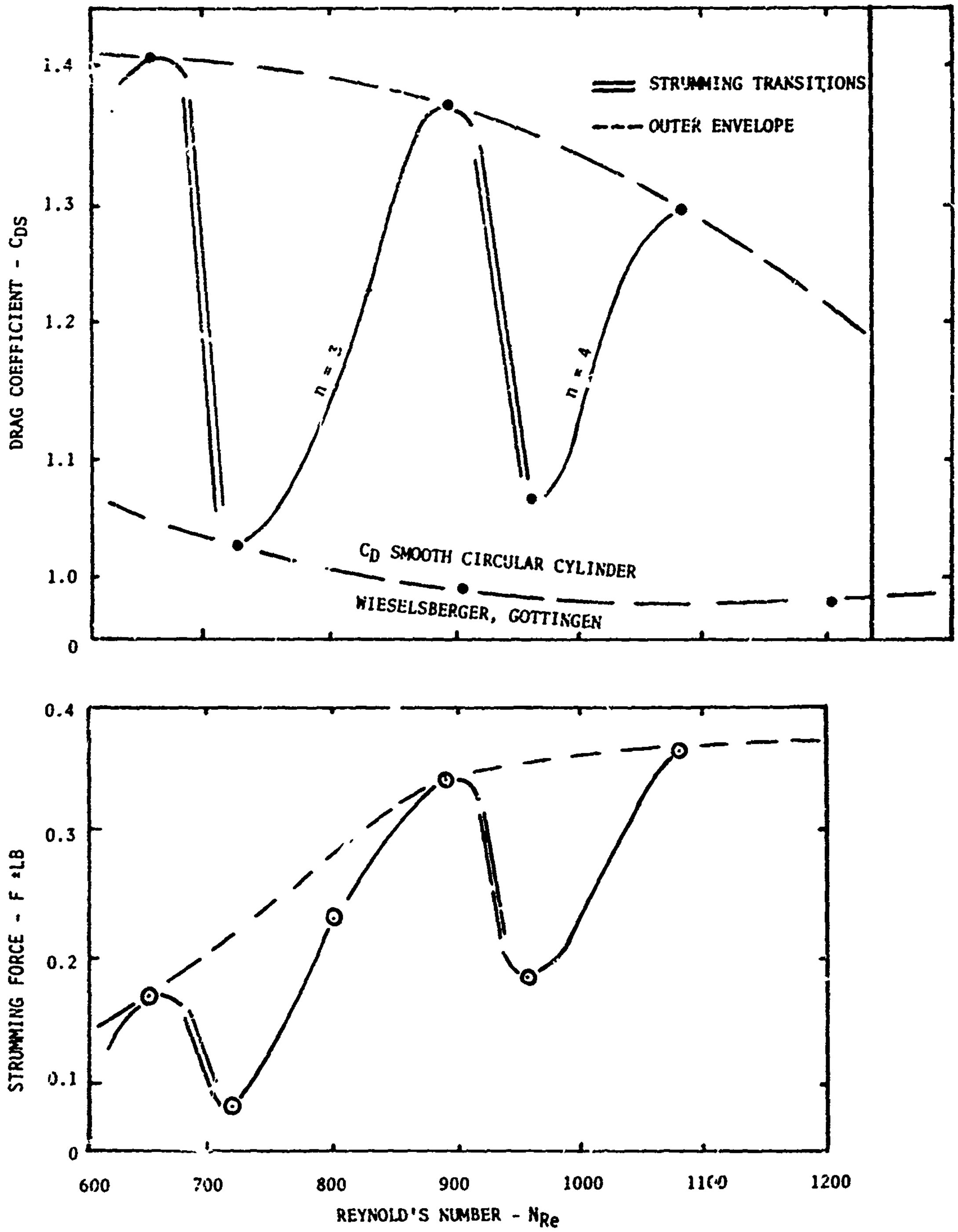


FIGURE 3 - Strumming Drag Coefficient and Force for a Smooth Cylindrical Cable 0.107 In. Diameter, 3 Ft Long

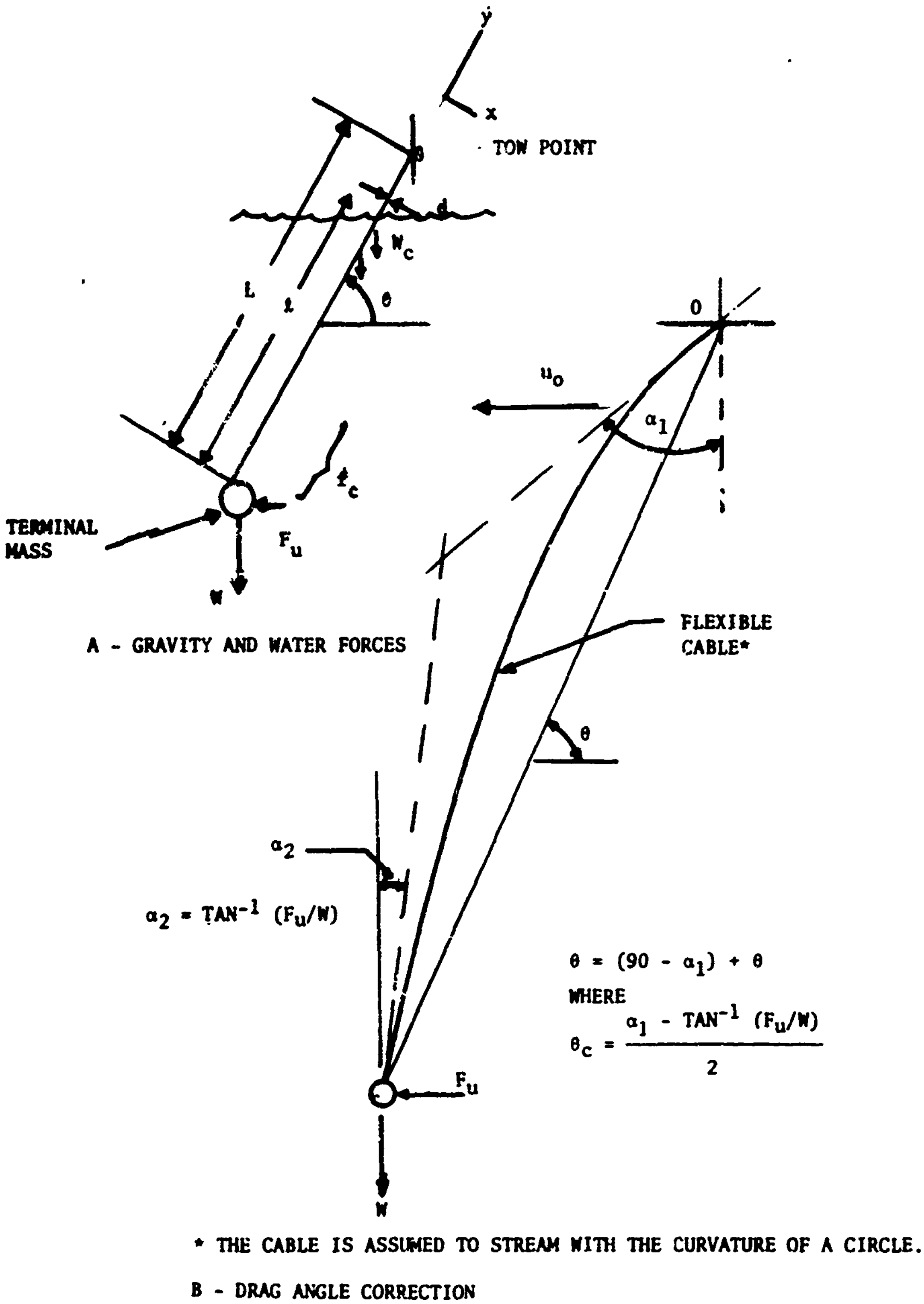


FIGURE 4 - Parametric Relations for the Streaming Flexible Cable

CABLE DRAG COEFFICIENT TEST CABLE 0.107 IN. DIA TEST NO. 1 DATE

EQUATIONS

$$f_c = W_c \cos\theta + \frac{W\cos\theta - F_u \sin\theta}{A} \; ; \; C_{DS} = \frac{f_c}{B\,(u_o \sin\theta)^2}$$

$$F_u = C_D \frac{\pi D^2 \rho}{8g} u_o^2 ; \; A = \ell\left(1 - \frac{\ell}{2L}\right); \; B = d\,\frac{\rho}{2g}\,(1.69)^2$$

SETUP CONSTANTS

$W = 0.5075$ LB (WATER WEIGHT)

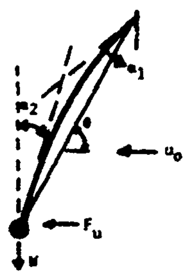
$W_c = 0.0019$ LB/FT (WATER WEIGHT)

$A = 1.79$ FT $\quad \ell = 3.00$ FT, $L = 3.71$ FT

$B = 0.0247 \frac{LB\text{-}SEC^2}{FT^3} \quad d = 0.0089$ FT

$F_u = 0.0444\, u_o^2 \quad D = 0.167$ FT, $C_D = 0.73$, u_o, KN

CABLE GEOMETRY



1. MEASURED PARAMETERS

α_1 °	u_o KN	f_s C/S
10.5	0.77	52

2. ANGLE CORRECTION

α_1	u_o^2	$F_u\, u_o^2$	$\tan^{-1}\frac{F_u}{W}$	α_2	θ_c $\frac{\alpha_1 - \alpha_2}{2}$	θ $(90 - \alpha_1) + \theta_c$
10.50	0.593	0.0263	0.0518	3.00	3.70	83.20

3. C_{DS} CALCULATION

$\cos\theta$	$\boxed{1}$ (W) $\cos\theta$	$\sin\theta$	$\boxed{2}$ $F_u \sin\theta$	$\boxed{3}$ $\boxed{1} - \boxed{2}$	$\boxed{4}$ $\frac{\boxed{3}}{(A)}$	$\boxed{5}$ $(W_c) \cos\theta$	f_c $\boxed{4} + \boxed{5}$	$\boxed{6}$ $(u_o \sin\theta)^2$	C_{DS} $\frac{f_c}{(B)\,\boxed{6}}$
0.118	0.0599	0.993	0.0261	0.0338	0.0189	0.00085	0.0197	0.583	1.37

NOTE:
- $\square$ REPRESENT CALCULATION NUMBER
- $\bigcirc$ ENTER VALUE OF CONSTANT

FIGURE 5 - Standard Data Sheet With Sample Calculation

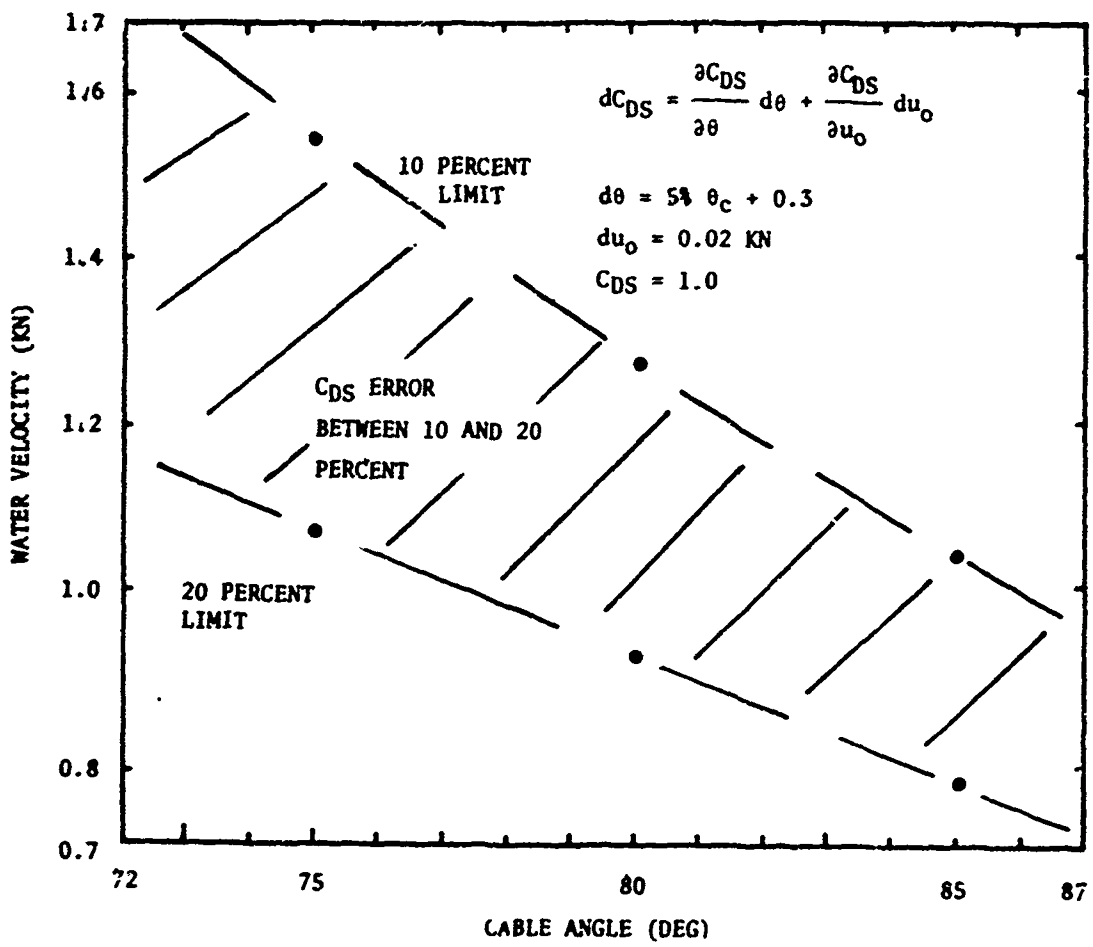


FIGURE 6 - Estimate of Strumming Drag Coefficient

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13 ABSTRACT

The determination of normal drag coefficients for flexible cables was developed to aid in a study of static cable drag dependence on cable strumming as related to underwater suspension cables used with airborne ASW sonar systems.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
FLEXIBLE CABLE						
DRAG COEFFICIENT						
STRUMMING						